NanoResolution MRS Sensor Delivers Fast, Precise 3D Inspection and Measurement for Advanced Semiconductor Packaging Applications

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The semiconductor packaging industry continues to advance, with new designs adding more layers, finer features and more I/O channels to achieve faster connections, higher bandwidth and lower power consumption. As packaging technologies have evolved, manufacturers have adapted old processes and adopted new processes to connect chips to each other and to the outside world. Often these new processes use front-end-like tools and techniques to perform back-end tasks, blurring the traditionally sharp distinction between the two ends. This area of overlap has been called the middle-end and its growing importance has created an increasing need for specialized, high-precision measurement and inspection capabilities to detect defects and improve process control. The new NanoResolution MRS (multiple reflection suppression) sensor uses phase shift profilometry, an automated optical inspection technology, to address these needs.

Advanced Packaging

Advanced packaging techniques are evolving rapidly and many different processes are used in different applications. In general, all seek to integrate more power and functionality in a single package that uses less space and has more numerous, shorter, faster connection paths. Most use some form of vertical integration (*figure 1*), stacking chips on top of each other or on specially designed substrates. Vertical connections are frequently made using bumps or pillars that extend above the surface of the chip. Because these processes use known good die, the cost of failure is high. The cost of failure can be even greater when the health and safety of the user is at risk, as in automotive applications for assisted driving or self-driving cars. Fast accurate inspection and measurement of these and other similar structures is a critical requirement for improving yields and ensuring reliability.

Figure 1 Advanced packaging processes integrate chips and substrates vertically to put more power and functionality in less space. Many advanced packaging processes use solder bumps and pillars for vertical connections. Source: Yole Developpment, Amkor.

Phase Shift Profilometry

Phase shift profilometry (PSP) uses structured light to measure three-dimensional (3D) objects. It projects a fringe pattern on the object and looks for shifts in the pattern that appear when surfaces at different heights are viewed from an angle to the projection direction. Figure 2 shows a schematic representation of the PSP principle and an example of a fringe pattern projected on flat surfaces of different heights. The intensity of the projected pattern varies sinusoidally across the fringes, permitting very precise measurements of shifts in the phase of the waveform.

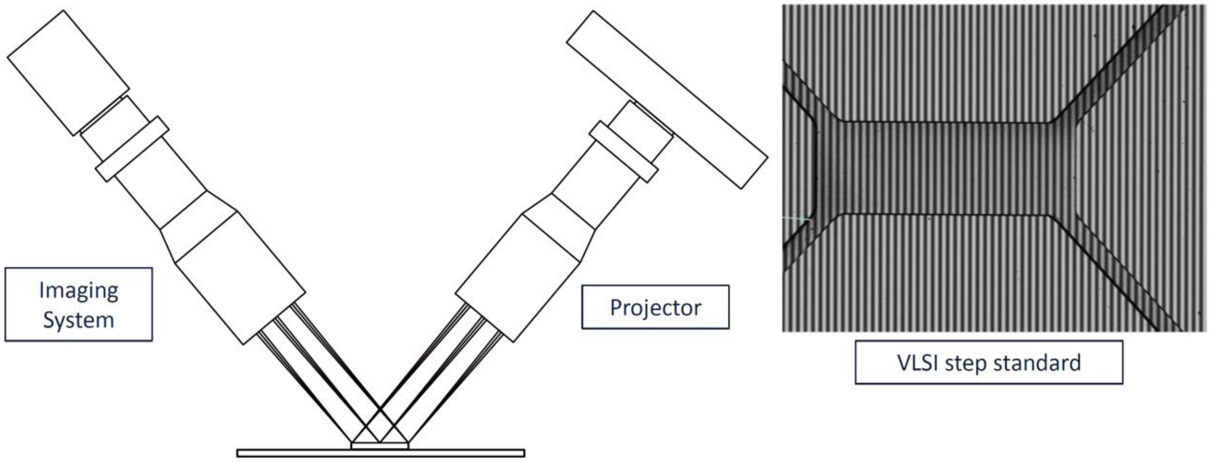

Figure 2 PSP projects a fringe pattern on the object and looks for shifts in the pattern that appear when viewed from an angle to the projection direction. The image on the right shows the shifts on a step standard containing surfaces at different heights.

There are three unknowns at each pixel in the image, phase (φ_0), which corresponds to the height of the surface, reflectivity (*R*), which is measured from a uniformly illuminated video image, and modulation (*m*) or fringe contrast. Three or more phase shifted fringe pattern images are acquired to solve equation 1 for the three unknown parameters at each pixel.

Eq. 1 $$I = \frac{I_0 R}{2}(1 + msin(2\pi f_x + \varphi_0))$$

Phase shift profilometry offers unparalleled speed and accuracy, with achievable data rates greater than 100 million 3D points per second and resolution scalable down to 1.5µm laterally and 25nm vertically. Importantly, for applications such as semiconductor packaging where production worthy throughput is critical, PSP can perform both 2D and 3D measurements in a single pass. It is widely used for 3D automated optical inspection (AOI) by electronics manufacturers assembling printed circuit boards (PCB) with surface mount technologies (SMT). It is also used for solder paste inspection (SPI) by PCB manufacturers (*figure 3*), and for dimensional measurements typically performed by coordinate measurement machines (CMM) in a variety of other industrial applications. PSP measurements are highly accurate and can be orders of magnitude faster than alternative methods.

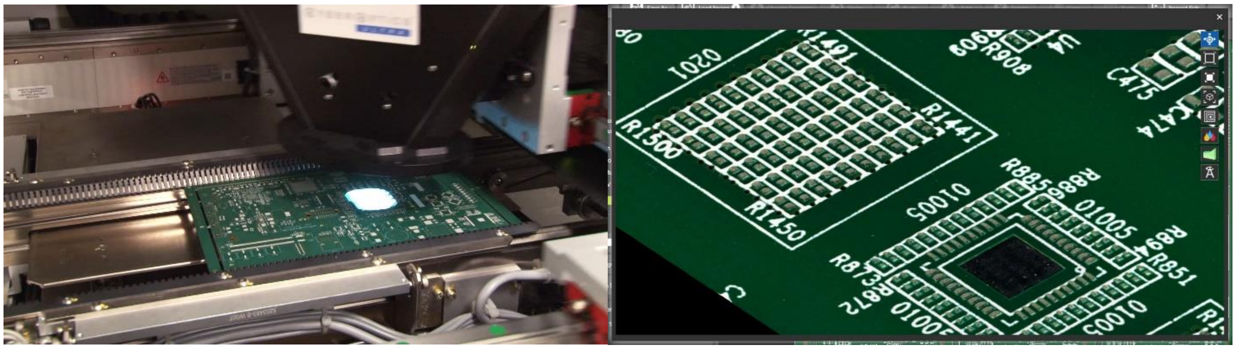

Figure 3 Phase Shift Profilometry is well proven and widely used to inspect printed circuit boards, surface mount technology components, and solder paste. This system is inspecting solder paste.

However, conventional PSP measurements can be significantly challenged by certain aspects of semiconductor applications. Shiny mirror-like surfaces can generate glints that saturate the camera or direct light completely away from the camera and create ambiguity between the height and tilt of the surface. Multiple specular reflections between shiny surfaces can cause inaccurate height measurements. Densely packed components, especially short components near taller ones, can occlude visibility of adjacent areas. The variety of features and materials with widely ranging reflectivities requires special treatment in the analysis. Finally, the system must be fast enough to inspect 100% of the wafer surface at production speeds of 25 wafers per hour or more.

Multiple Reflection Suppression

The CyberOptics MRS sensor (*figure* 4) addresses these challenges. The MRS sensor uses a single vertically positioned fringe projector, a coaxial camera for 2D measurements, and multiple cameras arranged off-axis around the projector to capture images for 3D measurements from different perspectives. The digital fringe projector can project images over a range of frequencies and orientations. The sensor uses fringe patterns of different frequencies and sophisticated "phase unwrapping" routines to achieve both fine resolution and extended range in vertical measurements. The use of a single projector and multiple cameras allows parallel data collection and unprecedented 3D measurement speed. Multiple views also ensure that none of the surface is hidden by adjacent tall features.

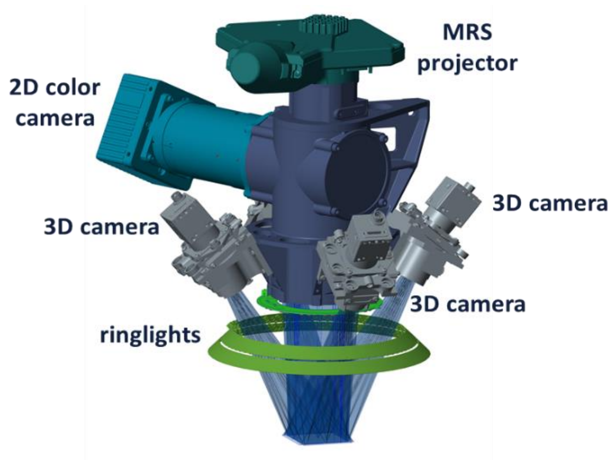

Figure 4 CyberOptics MRS sensors' unique optical architecture uses multiple cameras and simultaneous data acquisition to provide fast accurate 3D measurements.

Multiple reflections among shiny surfaces can cause errors in PSP measurements (*figure 5*). These spurious reflections will appear differently to different cameras and at different fringe frequencies. When the fringe spacing is of the same order as the physical spacing between the shiny features, the reflection can add coherently in the phase calculation. At higher fringe frequencies (more closely spaced fringes), the same reflection may reduce fringe contrast but will not affect the phase calculation (*figure 6*). A key attribute of the MRS sensor is its ability to suppress these measurement errors by comparing information from images obtained from different perspectives and at different fringe frequencies.

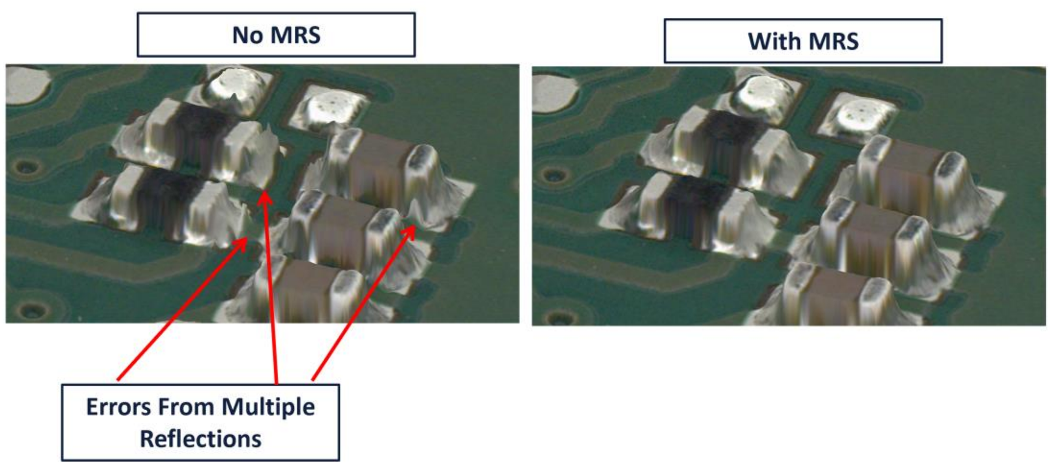

Figure 5 If not suppressed, multiple reflections between shiny components can cause errors in PSP measurements.

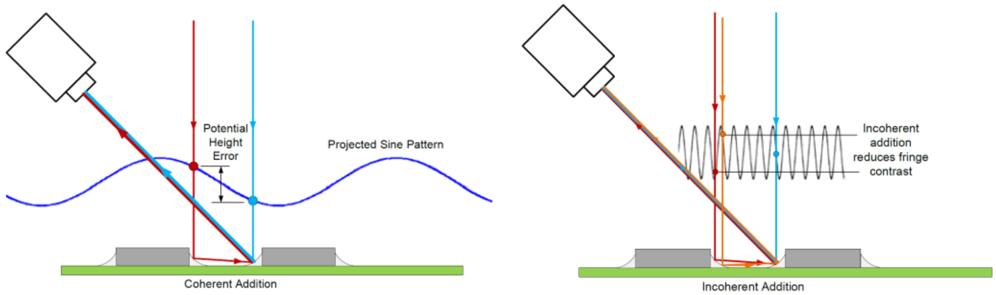

Figure 6 Multiple reflection errors can be suppressed by analysis from multiple directions at multiple frequencies. Reflections that add coherently at lower frequencies become incoherent at higher frequencies, reducing fringe contrast but not affecting the phase measurement.

NanoResolution MRS Sensor

A new NanoResolution MRS sensor has been developed for advanced packaging processes in the "middle-end" of the manufacturing process (*figure 7*).

Figure 7 The NanoResolution MRS sensor is suitable for a variety of applications found in middle-end advanced packaging processes.

The new sensor provides 50-nanometer height resolution and 0.2-micrometer accuracy on features as small as 25µm (*table 1*). And, while retaining its ability to reject spurious multiple reflections, it adds the ability to capture and analyze specular reflections from shiny surfaces of substrates, solder balls, bumps and pillars, thus allowing accurate inspection and 3D metrology of these critical packaging features. With data processing speeds as high as 75 million 3D points per second, it delivers production-worthy throughputs of 25 wafers (300mm) per hour and more.

Specification	PFS15
FOV (mm)	15 x 15
2D lateral resolution (µm)	3
Z height resolution (µm)	0.05
Accuracy (µm)	0.2
Repeatability (3σ)	1.0
Minimum lateral feature size (µm)	25
Inspection rate (3D points/sec)	75M
Inspection rate (WPH)	25+

Table 1 The new NanoResolution MRS sensor is designed for middle-end applications in advanced packaging processes.

Predictably, as advanced packaging technology has gained traction, the size and pitch of bumps and pillars has decreased and their number has increased *(figure 8*). Bumps for the C4/Flip Chip process, now a very mature process, are 75µm-200µm in diameter and similarly pitched. With the introduction of lead-free processes, size decreased somewhat to 75µm-150µm. Copper pillar processes, currently mainstream, decoupled bump height from diameter and allowed manufacturers to decrease diameters to 50µm-100µm. Next generation processes, some of which are coming on-line now, use µ-pillars with 10µm-30µm diameters. The new NanoResolution MRS sensor includes a high-resolution optical system with 3 µm lateral resolution, more than enough for bumps used in most current generation processes. One obstacle overcome by designers was the integration of high NA optical elements for multiple cameras in the limited available space. In principle, the technology can scale down to 1.5µm lateral resolutions.

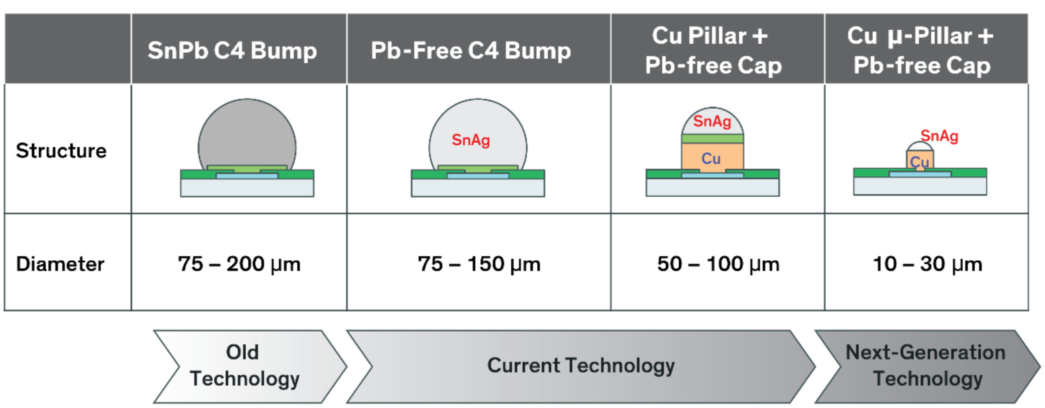

Figure 8 Source: Dow Chemicals. Bumps sizes and pitches are decreasing and the number of bumps per die is increasing. The new NanoResolution MRS sensor can support most current and next generation processes.

Critical parameters to be controlled in bump and pillar processes include bump height, position, diameter, shape, and coplanarity (*figure 9*). All are critical to ensure reliable connections. Reliability is an area of special concern for advanced packaging processes. Inter-chip connections have proven to be prone to field failures as the effects of thermal stress on disparate materials accumulate over time.Field failures are very costly for many reasons. They entail the return of finished devices containing costly known good die. They impact the reputation of the supplier with the customer. In some applications, they expose the user to health and safety risks and the device manufacturer to potential financial liability.

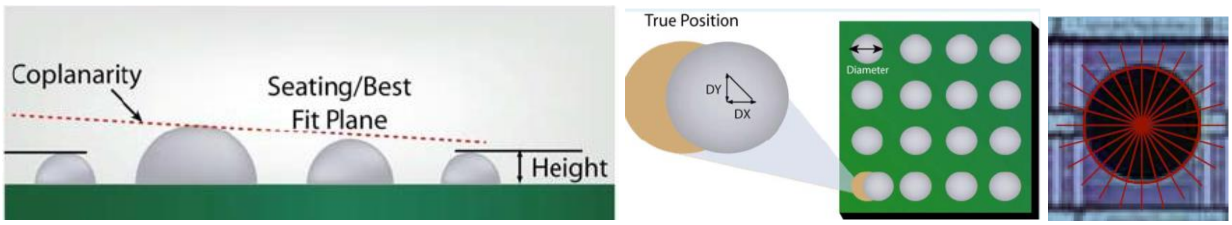

Figure 9 Parameters that must be controlled for bumping processes include height, coplanarity, position, size, and shape.

Many customers, especially in higher risk markets like automotive applications, are requiring 100% inspections. Other optical inspection technologies are challenged to provide 100% inspection with enough accuracy and precision at production throughputs and often use a sampling strategy, extrapolating measurements of a subset of features to characterize the whole population. Many also require separate passes for 2D and 3D measurements. The MRS sensor’s high speed and ability make both 2D and 3D measurements in a single pass allow it to deliver accurate, repeatable results from a single pass at throughputs in excess of 25 wafers per hour.

Specular Surfaces

Bumps and pillars typically have shiny, mirror-like surfaces. Many substrate materials also return specular reflections. As described above, the MRS sensor is designed to suppress errors caused by spurious multiple reflections from specular surfaces. The NanoResolution MRS sensor also includes an additional channel designed specifically to measure specular surfaces. Conventional fringe projection is challenged by these surfaces because it relies on variations in the intensity of a diffuse reflection, which is not available from a mirror-like surface. However, if the specular surface is treated as an optical element, distortions in the reflected pattern can be used to calculate the geometry of the surface (*figure 10*).

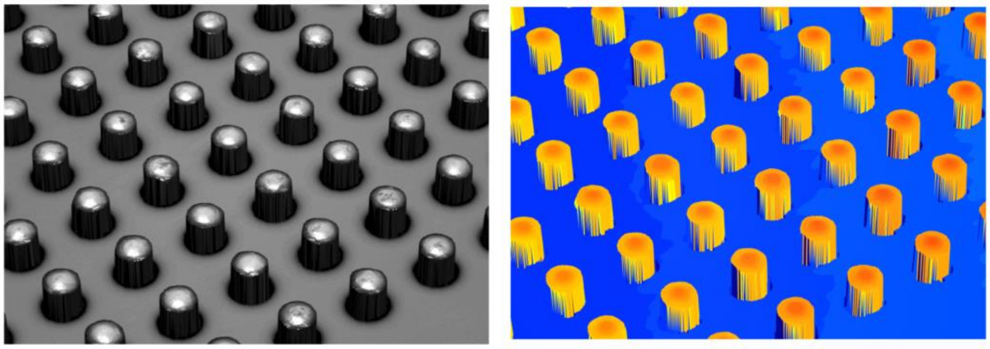

Figure 10 The NanoResolution MRS sensor is uniquely capable of using information in specular reflections to characterize shiny surfaces of bumps and pillars.

Conclusion

MRS fringe projection technology provides an unparalleled combination of speed and accuracy, faster than other optical inspection technologies. MRS technology suppresses errors caused by spurious multiple reflections from shiny components. The new NanoResolution sensor includes a separate measurement channel designed to use information contained in specular reflections to characterize shiny surfaces like those typically found on solder bumps and pillars. The new sensor offers 3µm lateral resolution and 50nm vertical resolution, and the technology can scale to 1.5µm lateral resolution and 25nm vertical resolution. MRS can perform both 2D and 3D measurements in a single pass. With data acquisition rates up to 75 million 3D data points per second, it can perform 100% inspection on 300mm wafers at a throughput of 25 wafer per hour, 2-3X faster than alternate technologies.

MRS technology is suitable for a wide variety of inspection and measurement applications, including printed circuit boards, surface mount technology components, solder paste, packaged circuits, and wafer bumps, as well as other industrial products typically measured by coordinate measurement machines. CyberOptics has a 30-year track record of designing, building, and supporting innovative, high-speed, high-accuracy optical sensors and measurement systems. The company also supplies sensors on an OEM basis to capital equipment manufacturers and precision automation suppliers.

Specification	NanoResolution MRS Sensor (2D + 3D)	Ultra-High Resolution MRS Sensor (2D & 3D)	MRS Sensor (2D+3D)	MRS Sensor (2D+3D)
Minimum Feature Diameter (µm)	25	110	130	180
FOV (mm)	15x15	21x21	26x26	36x36
3D Height Resolution (µm)	0.05	0.2	0.2	0.3
Repeatability (µm) (3σ)	1	3.5	4	5
Accuracy (µm)	0.2	1	1	1
3D Acquisition Time, typical (msec)	150	85	85	80

Table 2 MRS sensors come in a range of capabilities suitable for a variety of applications.